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SHORT-TERM TEMPORAL STUDIES OF THE X-RAY EMISSION FROM CAS A, TYCHO AND SCO X-1

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SHORT-TERM TEMPORAL STUDIES OF THE

X-RAY EMISSION FROM CAS A,

TYCHO AND SCO X-1

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ABSTRACT

No evidence for stable 2-10 keV periodic emission from Cas A or Tycho in the period range 1 msec to 10 sec is found. Upper limits to the pulsed fraction are presented as a function of the assumed light curve, with absolute 99% confidence upper limits of 0.089 and 0.195 for Cas A and Tycho, respectively. Previously reported transient 1-10 Hz oscillations from Sco X-1 are not observed.

An abbreviated version of this study has been submitted as a Letter to the Astrophysical Journal.

I. INTRODUCTION

The identification of pulsars with neutron star residuals of supernovae has given impetus to the search for pulsars at the locations of known supernovae in all energy bands. With the exception of the Crab and Gum Nebulae, however, such searches have been fruitless. In particular, both Cas A and Tycho have been investigated for radio (Reifenstein, Brundage and Staelin, 1969) and optical (Horowitz, Papaliolios and Carleton, 1971) pulsars without success. There remain, however, strong agruments for assuming the presence of contemporary energy sources (such as rotating neutron stars) in these remnants: the observed x-ray emission (Holt and Ramaty, 1970) and the secular variation of the Cas A radio luminosity (Cavaliere and Pacini, 1970). The present pulsar search of these remnants is the most sensitive yet undertaken in the x-ray band, utilizing data obtained from a rocket-borne proportional counter experiment launched from White Sands, New Mexico at 0900 UT on 19 May 1972.

Data from another rocket-borne proportional counter experiment, launched at 1000 UT on 3 March 1969, revealed no pulsar-like persistent oscillations from Sco X-1 (Boldt, Holt and Serlemitsos, 1971). A similar analysis (Angel, Kestenbaum and Novick, 1971) likewise yielded no persistent periodic emission, but uncovered evidence for short-term (~ one minute duration) oscillatory modes in the range 1-10 Hz. The 1969 data are reinvestigated in an attempt to confirm the reported effect.

II. CAS A AND TYCHO

Two separate methods were employed in searching for periodic behavior in the present data: direct fast-folding and Fourier decomposition. Applying straightforward χ^2 considerations to a fast-fold algorithm, an upper limit to the presence of periodic modulation of the data stream at any specified period may be set at a confidence level equivalent to n sigma from

$$\left(\frac{f}{1+f}\right)^2 = \left(\frac{\beta}{1-\beta}\right) \frac{n\sqrt{2P}}{N}, \qquad (1)$$

where f is the ratio of events in the periodic conponent of the data stream to those in the temporally stable component, β is the fractional duty cycle of the periodic component, P is the number of temporal bins per period ($\gtrsim$ 40 for equation (1) to apply) and N is the number of photons counted (Boldt, Holt and Serlemitsos, 1971). In order to avoid missing significant structure, the algorithm folds the data at many more trial periods than the number of truly independent ones. Therefore, equation (1) may also be used to determine an upper limit to any periodic component so long as N is large enough such that the probability of it being exceeded by random data is small compared to the inverse of the number of independent period trials.

Fourier decomposition (power spectral analysis) is a bit less sensitive than folding at low frequencies, but has the advantages of computational ease and speed as well as strict orthogonality between all the frequency components tested. For a stream of k strictly random data, the probability of exceeding any Fourier amplitude A is given by

$$\mathrm{Prob}\left\{({a_n}^2 + {b_n}^2) > A^2\right\} = \exp\left(-\frac{A^2k^2}{4N}\right). \qquad (2)$$

In comparing with equation (1), the use of a <u>single</u> amplitude (i.e., primary frequency component alone) for placing an upper limit results in

$$f = \frac{\alpha\beta k}{N} = \frac{\pi A\beta k}{\sqrt{2(1-\cos 2\pi\beta)}\, N} \approx \frac{Ak}{\sqrt{2}\, N}, \qquad (3)$$

where α is the actual increase in counting rate during the disturbance "on-time", and k is the total number of records which result in N total counts. Note that since $\pi\beta$ is a reasonable approximation to $\sqrt{1-\cos 2\pi\beta}$ (i.e. always within 25%), the detectable pulsed fraction is independent of pulse width if only the primary frequency component is tested. Therefore, the a priori probability of obtaining an amplitude A corresponding to a pulsed fraction f for a given N random events may be written

$$p \approx \exp\left(-\frac{Nf^2}{2}\right) , \tag{4}$$

so that demanding 99% confidence that there is no true periodicity in the data at a specific frequency implies

$$f^2 \leq \frac{9.2}{N} . \tag{5}$$

Since there are $\frac{k}{2}$ independent Fourier components, the 99% confidence condition that there is no true periodicity at any frequency whatsoever is

$$f^2 \leq \frac{-2}{N} \ln\left(\frac{2 \times 10^{-2}}{k}\right) , \tag{6}$$

if no significant power is observed.

The analyzed data consist of a 62 second exposure to Cas A and a 98 second exposure to Tycho. In all, there are 6428 nonzero events in the Cas A sample (of which ~ 80% may be attributed to the source itself) and 3684 events from the extended stop at Tycho (~ 50% from the source). The sampling time of the experiment is 320 μsec (see Boldt, Desai and Holt, 1969, for a complete description of the temporal characteristics of the telemetry system). Unfortunately, a malfunction in the telemetry coding resulted in the loss of words 1, 2, 33 and 34 out of every 64-word frame, but this artifact in the data record did not seriously affect the temporal analysis, as will be shown below.

The condition for the systematic telemetry disturbance being in phase with a trial period is

$$P = 32 \frac{m}{q} , \tag{7}$$

where m and q must both be integers. The problem is, of course, less severe as the integers become larger, but all of these artifically induced periodicities are extremely narrow band (and completely deterministic), so that the gaps in coverage necessitated by this effect constitute a trivial fraction of the total range investigated.

For the Cas A record, the fast-fold algorithm used a maximum of 10^5 data intervals per pass compared with a total of 1.92×10^5 320 μsec intervals in the Cas A exposure. For $P > 80$, the data were compressed by a factor of two by adding pairs of intervals together so that all periods between 12.8 msec and 13.1 sec could be run with $40 \leq P \leq 80$. Note that after the fifth compression (i.e., for periods in excess of .4096 seconds), there is no longer any remnant whatsoever of the systematic disturbance to contaminate the record. There were no $\gtrsim 5\sigma$ results which could not be directly attributed to this disturbance in the above period range (in the low period portion, where more than one pass was required, the results were combined for equivalence with a single pass using all the data). The upper limit to any periodic modulation of the data is then given by equation (1), with n =4.8, and graphically displayed in Figure 1 with the correction to equation (1) being made in recognition of the fact that only 80% of N can be attributed to Cas A. As the number of independent Fourier periodic components in the entire record is $\sim 10^5$, and as the folding routine tests only the lowest 5% of these frequency components (i.e., $P \geq 40$), the 4.8σ stipulation on any individual component is, in effect, equivalent to an upper limit at the 99% confidence level for any periods in the range 12.8 msec to 13.1 sec.

Using the Fourier-decomposition approach, the data were broken into six seperate 10.49 sec samples (with .095 Hz resolution) and examined individually for any disturbances with a probability (see equation (2)) of 10^{-6}, as the number of independent components in each sample is 1.6×10^4. The only such periodicity thus encountered was at the systematically induced telemetry disturbance and its harmonics (up to the 6th at this level of detectability). Note that f and β for this disturbance may formally be defined (both are .0625), so that the upper limits displayed in Figure 1 are entirely realistic (e.g., the fast-fold algorithm detects the disturbance at $n > 20$). Tests were also run with simulated periodicities inserted with Poisson counting statistics to assure the validity of the upper limits.

As the probability thresholds in Table I were actually obtained directly from the variance of the Fourier amplitudes in each trial, a further consistency check was the equivalence of the distribution with that calculated from equation (2), i.e. the total number of events N calculated from the amplitude variance with the assumption of random data in is agreement with that actually observed. The artifact periodicity at 10.24 msec was not subtracted from the Table I data, which accounts for the slight excess in peaks for $p < .01$.

As each of the six Cas A Fourier decompositions are completely independent, they can be investigated for coincidences at probabilities much greater than 10^{-6}. We can determine the net probability ϕ for the number of successes s in a number of trials t, where the probability for success is that of equation (2) for each individual trial:

$$\phi(s,t) = \frac{t!}{s!\ (t-s)!}\ p^s(1-p)^{t-s}. \tag{8}$$

The overall probability distribution in each trial was consistent with that expected, but there was one period value for which ϕ was found to be statistically significant. At a frequency of $851.82 \pm .05$ Hz, a three-fold coincidence was obtained in the six trials at a probability threshold of 5×10^{-3}, yielding a net probability ϕ of 2.5×10^{-6}, which then corresponds to an overall probability of only .04 that the effect is a random artifact (as there are 1.6×10^4 such frequency components). This could not be checked with folding as the period of 1.17 msec is too short to effectively get a light curve with 320 μsec bins. We could, however, check the phase consistency of the result by repeating the whole procedure with a different temporal grid. Beginning 4 seconds later, none of the five resultant 10.49 sec trials yielded any significant power (i.e. $p < .04$) at this frequency, so that it is concluded that the apparent periodicity at 1.17 msec detected at 96% confidence initially is almost certainly accidental.

III. Sco X-1

The same telemetry system was employed in this experiment, except that the word time was 322 μsec instead of 320 μsec, and there was no malfunction as in the 1972 flight. There was, however, another systematic effect which limited the temporal analysis: during the course of the exposure (which lasted in excess of two minutes) the detector aperture was modulated with a passive collimator having five discrete positions, each with dwell times of 2.7 sec. Therefore, the data stream was modulated at a primary frequency of 13.4 sec with an amplitude of $\sim$ 20%. This effect could easily be eliminated from an analysis for persistent oscillations, and we have already reported upper limits for such periodic emission from the fast-fold analysis in the range 3-300 msec. The Fourier analysis similarly yields approximately 1% pulsed fraction as a 99% upper limit in the range 644 μsec to 1.31 sec.

In looking for transient periodic oscillations in the 1-10 Hz range the data were broken up into twelve independent 10.55 sec trials and analyzed in a manner identical to the Cas A Fourier analysis. Although the overall distribution of independent amplitudes was consistent with no marked periodic modulation (see Table II), the 1-18 Hz region had approximately 50% more peaks than expected from random data. We surmise, however, that this additional low frequency power is systematically induced from the detector modulation and rocket motion. One characteristic of this anomaly is the fact that the disagreement between the number of expected and observed peaks decreases with increasing frequency, indicating that the peaks correspond to fundamentals at frequencies below 1 Hz. A second characteristic is the fact that more coincidences between peaks having $p < 0.04$ in adjacent runs are obtained than would be expected if there were no systematic modulation of the signal; we observe 6, while we would expect 0.7. Angel, Kestenbaum and Novick (1971) used this effect in their data as strong evidence that true transient periodicity was being observed but, unlike their data, in this case the number of coincidences remains higher than expected even for widely separated trials, e. g. the number of coincidences for any two of the 12 trials with starting times 73.86 sec apart is 5, while we would expect to observe 0.4.

The most likely explanation for this effect in the present data is experiment-induced systematics. We should expect extra low frequency power due to a variety of low frequency rocket functions (e. g. the detector modulation fundamental is at 0.075 Hz). Similarly, peak coincidences should be more frequent than for random data, but without the phase coherence of a persistent fixed periodicity. We can exclude persistent periodicity over the whole exposure down to the ~ 1% quoted above, but it remains to examine the possibility of recurrent bursts from the source only a few tens of cycles in duration.

This latter hypotheses was investigated by dividing the record into 49 independent 1.3 sec samples centered in the 2.7 sec modulator dwell times, so that these trials should be free of the systematics in the longer trials. 56 peaks were found in the 1-18 Hz range with $p< 0.04$, corresponding to an amplitide of 6.2% (the same probability threshold in the longer trials corresponded to 2.2%). In this case, both the total number of peaks obtained and the number of frequency coincidences were in agreement with what would be expected from random data.

IV. DISCUSSION

The upper limits displayed in Figure 1 for x-ray periodicity from Cas A and Tycho are considerably lower than previously reported. Gorenstein, Kellogg and Gursky (1970) have placed upper limits of 15% and 19% on Cas A and Tycho, respectively, but only in the period range 8-35 msec and for β=0.1 (the present limits for β=0.1 at 99% confidence are 3.9% and 8.4%). Over the range 1 msec-10 sec, the 99% confidence limits are 8.9% and 19.5% for $\beta >$ 0.35, and appropriately lower for smaller β.

If we consider a specific pulsar emission model, such as that proposed by Bertotti, Cavaliere and Pacini (1969), rotating neutron stars within the remnants are not denied by the above upper limits. Even if the earth is within the hypothesized pulsar "beam", the x-ray pulsed fraction could easily be less than 1%, particularly if the rotation period is longer than that of the Crab pulsar (Holt and Ramaty, 1970; Pacini, 1971).

With regard to persistent periodic emission from Sco X-1, the 1% upper limit at 99% confidence reported in Boldt, Holt and Serlemitsos (1971) has been verified with an independent analysis. As in the case of the Cas A and Tycho limits, the previously reported folding procedure gives lower limits for non-sinusoidal pulse profiles.

We find no evidence for intermittent 1-10 Hz periodic disturbances, such as those reported by Angel, Kestenbaum and Novick (1971), who deduced pseudo-periodic distrubances analogous, but much lower in amplitude, to those observed from Cyg X-1 (e. g. Holt, et al, 1971; Schreier, et al, 1972). Experiment systematics limited the present analysis to a threshold amplitude of 6.2% for the weakest of the 56 peaks considered, in contrast to the typical 1-2% amplitudes found by Angel, Kestenbaum and Novick in analyzing a similar number of peaks for coincidences; a threshold below 1% in the present analysis results in fewer than ten peaks, too small a sample for the lack of observed coincidences to be meaningful.

We must conclude that at the time of our observation any short-term low frequency oscillatory modulation of the x-ray emission had amplitude $\lesssim$ 2% if it lasted as long as the $\sim$ 1 minute persistence time deduced by Angel, Kestenbaum and Novick. If the persistence time was as small as $\sim$ 10 sec, the limit is $\lesssim$ 5% (note that the reported 1-2% amplitudes must be raised to at least this level if the duration time is lowered). Any smaller time scale would be both inconsistent with the Angel, Kestenbaum and Novick results and involve too small a number of cycles to be truly oscillatory.

TABLE I. Comparison of Observed Probability Distributions in 10.49 sec Fourier Analyses of Cas A with That Expected from Random Data

		$p < .04$	$p < .02$	$p < .01$	$p < .001$	$p < .0001$
Expected		656	328	164	16.4	1.6
Trial	1	682	361	193	21	2
	2	654	338	172	17	1
	3	673	364	191	21	2
	4	637	318	165	22	2
	5	645	332	168	17	3
	6	663	338	175	22	1

TABLE II. Comparison of Observed Probability Distributions in 10.55 sec Fourier Analyses of Sco X-1 with That Expected from Random Data

		$p < .04$	$p < .02$	$p < .01$	$p < .001$	$p < .0001$
Expected > 1Hz		649	325	163	16.3	1.6
Trial	1	669	328	169	25	2
	2	660	323	170	18	4
	3	648	340	172	22	3
	4	642	333	157	13	0
	5	653	329	164	29	1
	6	676	335	172	17	2
	7	643	325	164	18	3
	8	667	351	175	20	0
	9	664	335	172	16	3
	10	666	331	180	17	3
	11	681	349	169	23	3
	12	665	330	167	16	1
Total Expected in 1-18 Hz band				22	2.2	0.2
Total Observed in 1-18 Hz band				37	9	2
Total Expected below 1 Hz						0.01
Total Observed below 1 Hz						38

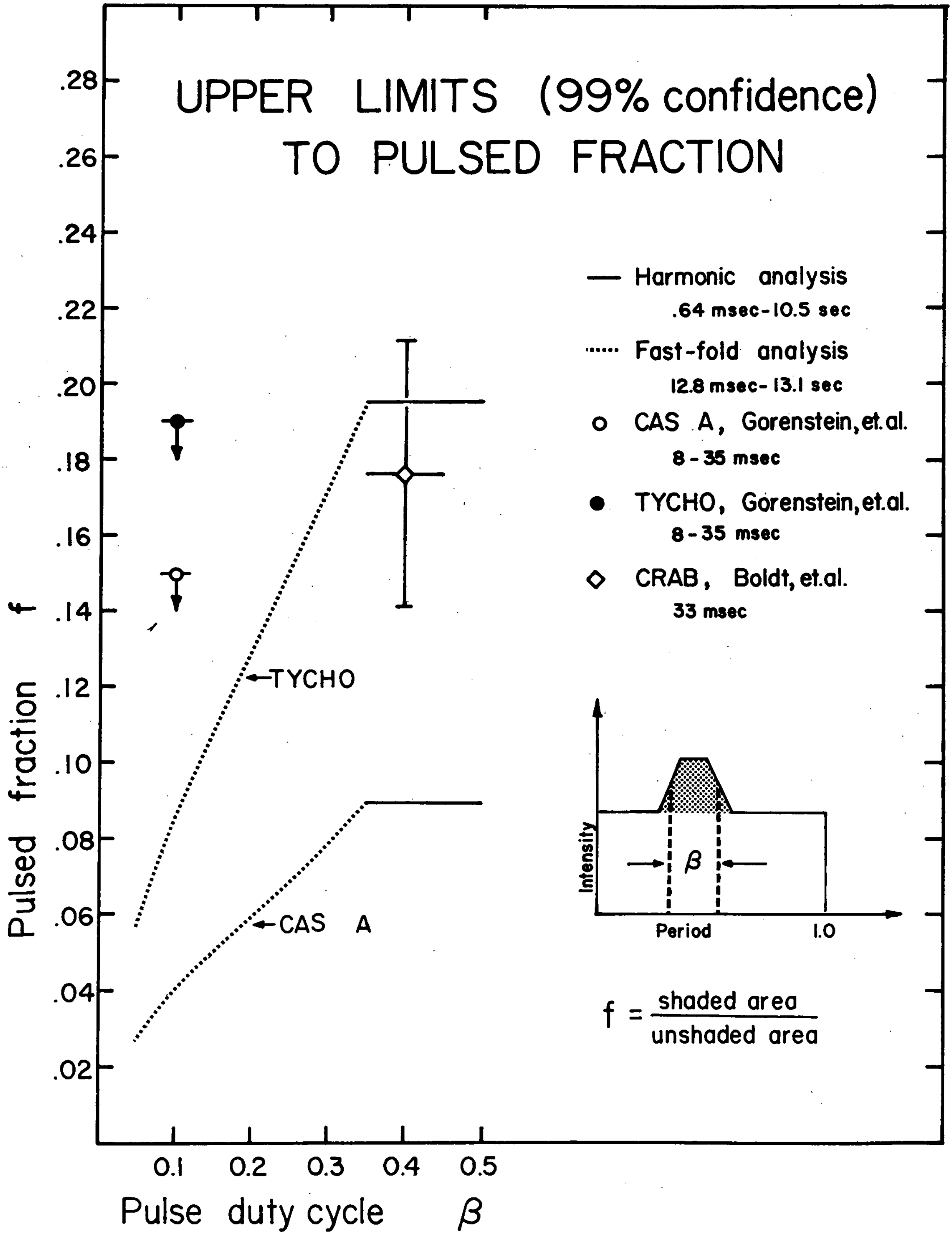
UPPER LIMITS (99% confidence)
TO PULSED FRACTION
Harmonic analysis
.64 msec-10.5 sec
Fast-fold analysis
12.8 msec-13.1 sec
CAS A, Gorenstein, et. al.
8-35 msec
TYCHO, Gorenstein, et. al.
8-35 msec
CRAB, Boldt, et. al.
33 msec
TYCHO
CAS A
Intensity
β
Period
1.0
f = shaded area / unshaded area
Pulsed fraction f
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0.1
0.2
0.3
0.4
0.5
Pulse duty cycle β

FIGURE 1

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